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Report #956541-Extension No. 2

RESEARCH AND DEVELOPMENT
ACTIVITIES IN
UNIFIED CONTROL/STRUCTURE MODELING AND DESIGN

By:

Arunkumar P. Nayak, PhD.

3 May 1985

JPL Contract No. 956541

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology and was sponsored by the National Aeronautics and Space Administration under Contract NAS 7-918.

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ABSTRACT

This report summarizes results of work sponsored by JPL and other organizations to develop a unified control/structures modeling and design capability for large space structures. Recent analytical results are presented to demonstrate the significant interdependence between structural and control properties. A new design methodology is suggested in which the structure, material properties, dynamic model and control design are all optimized simultaneously. The development of a methodology for global design optimization is recommended as a long-term goal. It is suggested that this methodology should be incorporated into computer aided engineering programs, which eventually will be supplemented by an expert system to aid design optimization. Recommendations are also presented for near-term research activities at JPL. The key recommendation is to continue the development of integrated dynamic modeling/control design techniques, with special attention given to the development of structural models specially tailored to support design.

The report is presented in vu-graph format. Each vu-graph is described in facing page text.

TRADITIONAL SPACECRAFT DESIGN METHODOLOGY

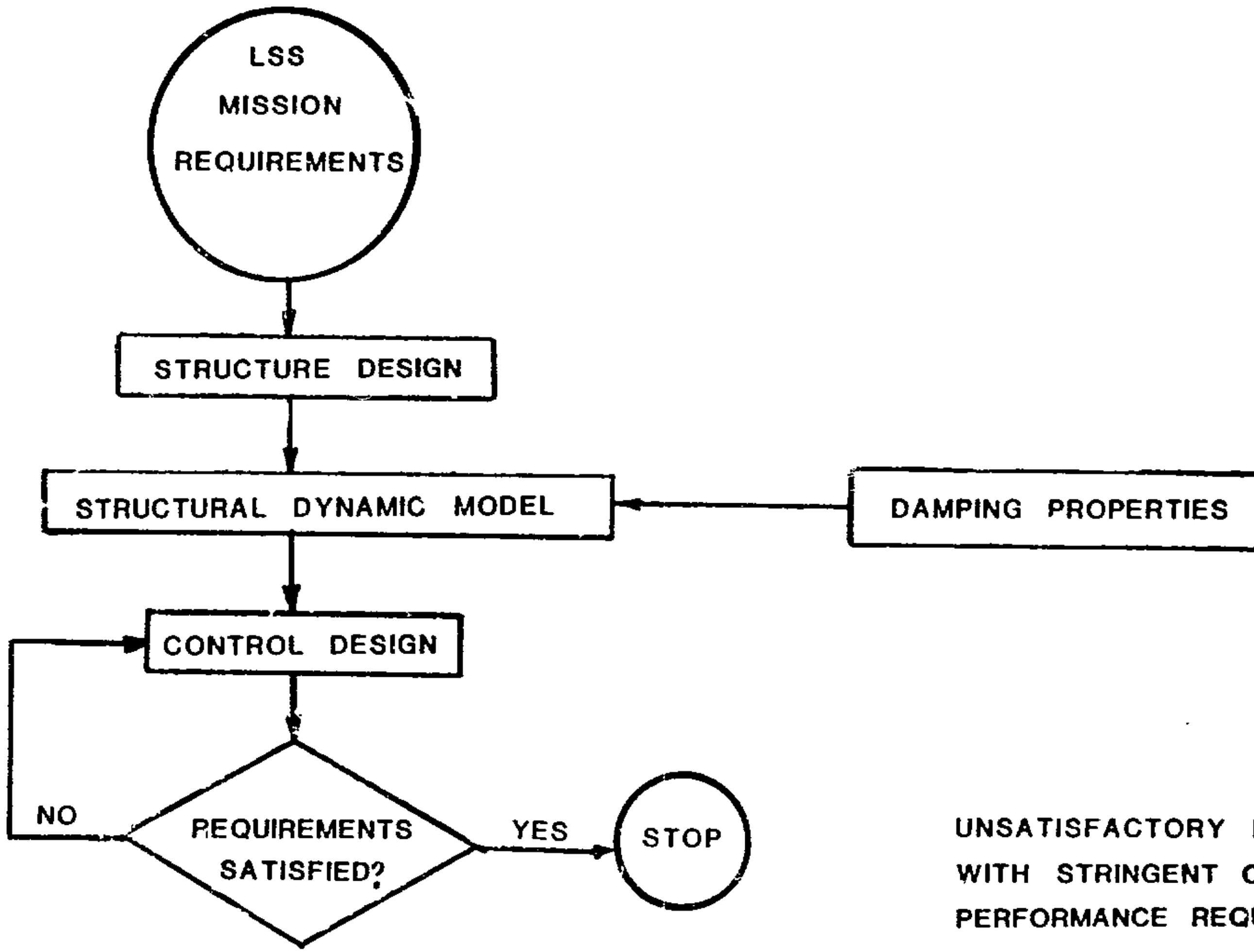
Traditionally spacecraft structures are designed in a straightforward manner. The structural configuration is selected to satisfy mission requirements and operational design conditions, such as boost loads, deployment and on-orbit maneuver loads. Sometimes additional design conditions are imposed to limit static and dynamic deflections. For example, a near-zero coefficient of thermal expansion may be required to limit shape errors, and a minimum vibration frequency may be imposed to prevent excessive dynamic interactions between the attitude control system and structure. This approach leads to a robust structural design that is not necessarily optimum.

A structural dynamic model is generated which is assumed to be sufficient to correctly predict spacecraft dynamic characteristics. A control design is obtained based on this model. A closed loop analysis and simulation are performed to determine if mission requirements are satisfied. The control design is iterated until satisfactory performance is achieved.

This methodology has worked well for many space missions. But the future large space structures may not be amenable to this design methodology. As higher performance is demanded, there is a stronger interaction between the structural modes and the controller. Therefore, the traditional design methodology, which did not emphasize the interaction, fails to obtain satisfactory results.

NASA and the Air Force appointed committees to study the control problem. A brief summary of an important NASA committee report appears in the next chart.

TRADITIONAL SPACECRAFT DESIGN METHODOLOGY



UNSATISFACTORY FOR LSS
WITH STRINGENT CONTROL
PERFORMANCE REQUIREMENTS

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EXCERPTS FROM NASA REPORT ON CONTROLS/STRUCTURES INTERACTION

NASA appointed a committee to study the problem of controlling a LSS. A final report of the NASA Space Systems and Technology Advisory Committee Ad Hoc Subcommittee on Controls/Structures Interaction was published in June 1983.

A partial list of structural dynamic/control interaction technology issues is taken from this report, Reference (1). The list indicates some of the problems in designing a control system. The problems identified by the committee, but not listed on the chart, are sensors and actuators development, digital implementation, ground and on-orbit testing. The Guidance and the Control Panel of the recent Air Force Military Space Systems Technology Model Workshop has also arrived at similar conclusions.

The next few charts show some recent results which give some clues to solve the control design problem.

Reference:

(1) Final Report on the NASA Space Systems and Technology Advisory Committee Ad Hoc Subcommittee on Controls/Structures Interaction, June 1983.

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EXCERPTS FROM NASA REPORT ON CONTROLS/STRUCTURES INTERACTIONS

NEED	PROBLEMS	COMMENTS
ANALYTICAL MODELS	INSUFFICIENT ACCURACY	FUNDAMENTAL PROBLEM
MODEL REDUCTION	TRUNCATION INTRODUCES ERRORS THAT MAY BE UNACCEPTABLE	TECHNOLOGY NOT MATURE
STRUCTURAL CONFIGURATION	LOW FREQUENCY MODES INTERACT WITH CONTROL SYSTEMS; STRUCTURAL DISTORTIONS CAUSE UNACCEPTABLE ERRORS; STRUCTURAL BEHAVIOR IS DIFFICULT TO PREDICT	LITTLE HAS BEEN DONE TO DEVELOP STRUCTURAL DESIGN APPROACHES THAT ALLEVIATE THESE PROBLEMS
CONTROL LAW DESIGN METHODOLOGY	FINITE CONTROLLER MUST CONTROL INFINITE DIMENSIONAL PLANT; ACCOMMODATION OF UNCERTAIN PLANT PARAMETERS; LOCATING ACTUATORS AND SENSORS; MANY MODES CLUSTERED IN A SMALL FREQUENCY BAND	TECHNIQUES HAVE BEEN GENERATED, BUT THEIR CAPABILITIES HAVE NOT BEEN VERIFIED ON REALISTIC STRUCTURES

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RECENT RESULTS:
EFFECT OF DYNAMIC MODELING ON CONTROL OF LSS

The two figures are taken from Reference (2). The figure on the left shows a top view of an idealized version of a wrap-rib antenna. The antenna consists of a rigid hub with 8 beam-like ribs cantilevered to it. The antenna is covered with a circular mesh that is tied to all the ribs and the hub. Two control torquers are placed on the hub perpendicular to each other. The sensors at the tip of each rib measure position displacements while sensors on the hub measure the angular displacements. The figure on the right shows a snapshot of an out-of-plane vibrating antenna. The information below the figures pertains to the physical values used in the modeling of the out-of-plane motion of the antenna.

A number of control analyses and modeling techniques were applied to this model to develop an understanding of the effect of dynamic modeling on control performance. The next two charts show some of the results obtained in this research.

Reference:

(2) HR Textron/UCLA Report #956541-Extension Final, Integrated Control/Structure Research for Large Space Structures, March 1985.

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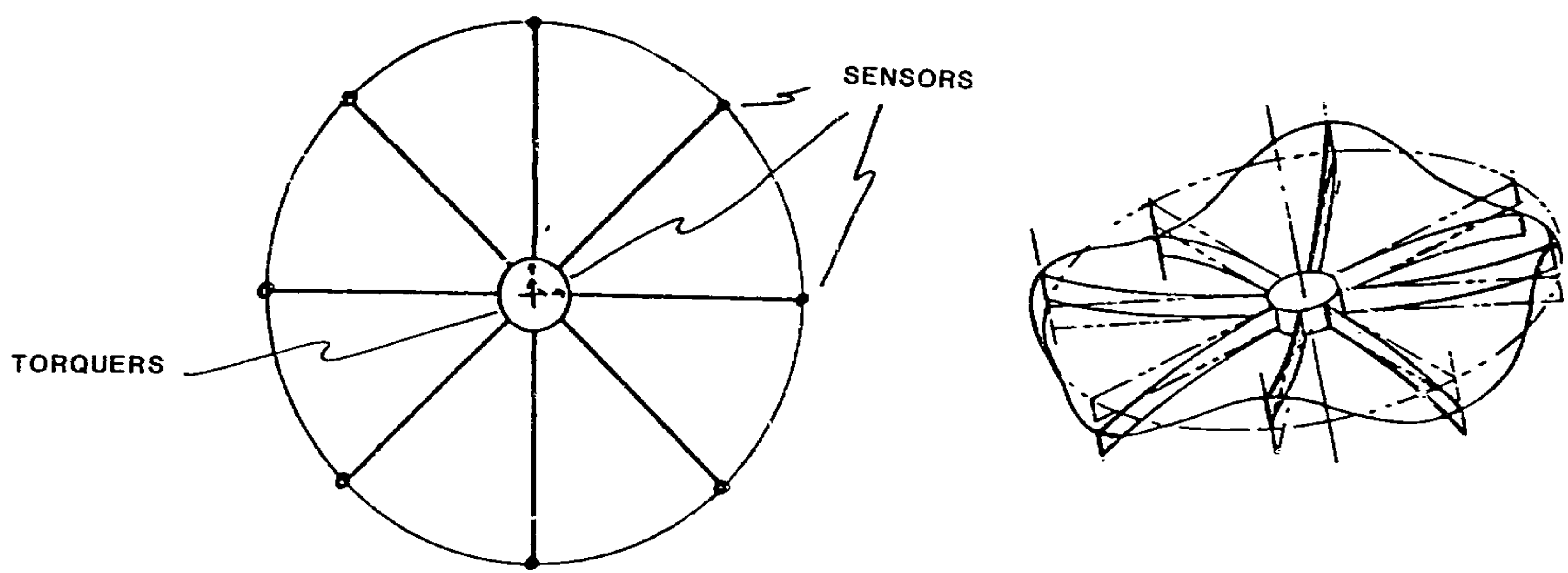
RECENT RESULTS:

EFFECT OF DYNAMIC MODELING ON CONTROL OF LSS



MODEL BASED ON WRAP-RIB ANTENNA DESIGN

HUB RADIUS = 46 in. RIB LENGTH = 86 ft.

HUB WEIGHT = 1000 lbs. RIB WEIGHT = 115 lbs. EACH

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RECENT RESULTS:
EFFECT OF DYNAMIC MODELING ON CONTROL OF LSS (Continued)

The figures show the control profiles of the torquer which tries to minimize the mean square surface error of the antenna. The control law is derived using Linear Quadratic Gaussian methods. The control profile in the figure on the left is due to a control law based on an 8-mode model. The vibrations have not been damped out until 25 seconds. The figure on the right is due to a control law based on a 22-mode model. Here the vibrations are damped in about 11 seconds.

The control profiles suggest that a higher dimension model produces better control. This means that a good model is essential for a good control.

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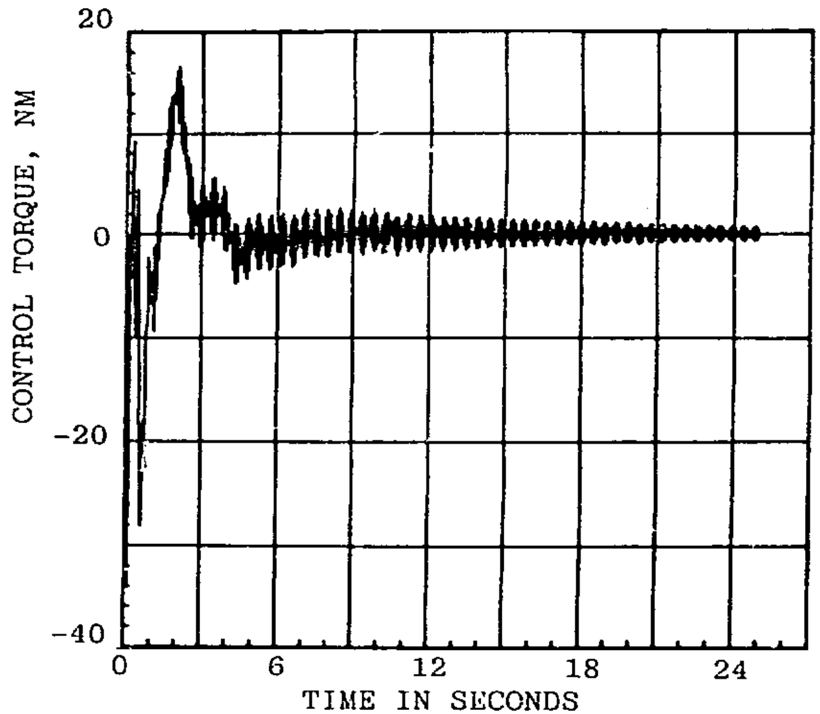
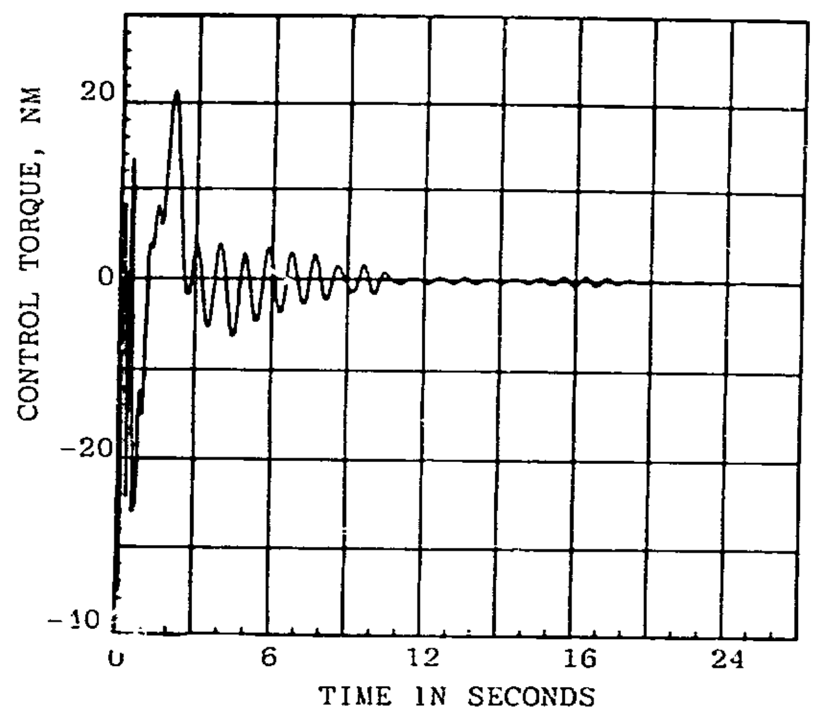
RECENT RESULTS:

EFFECT OF DYNAMIC MODELING ON CONTROL OF LSS (Continued)



8-MODE COMPENSATOR



22-MODE COMPENSATOR

RECENT RESULTS:
EFFECT OF DYNAMIC MODELING ON CONTROL OF LSS (Continued)

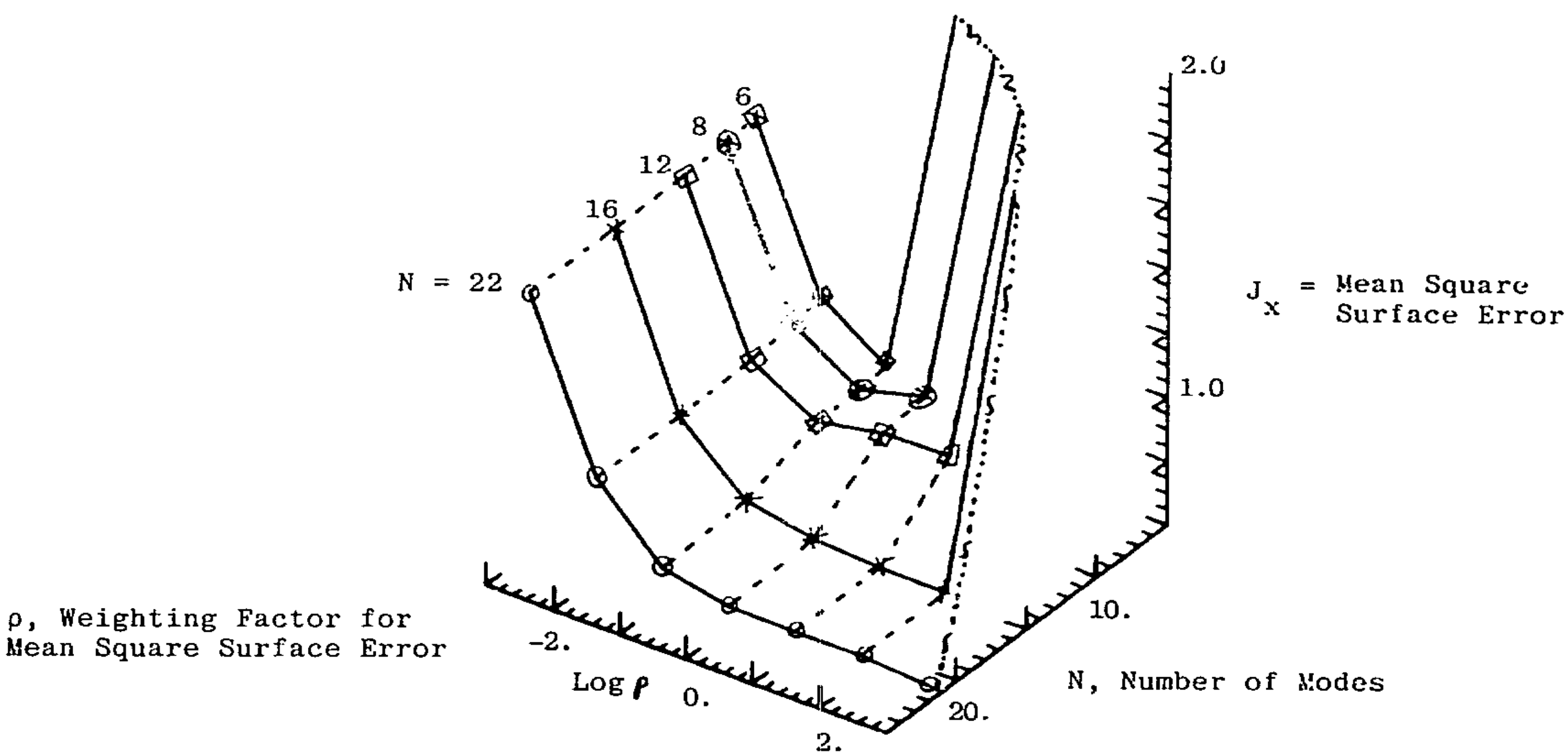
The three-dimensional plot shows the relationship of J_x, the mean square of the surface error of the antenna, to N, the number of modes included in the model on which the compensator is based, and ρ, the weighting factor of the surface error term in the optimization criterion.

The figure shows that when high performance is needed, i.e., ρ is high, a higher dimension model is required. For high ρ values, a control based on low dimension model is not adequate and sometimes the closed loop system can be unstable. For example, for $\rho = 100$, a controller based on 12 or less modes produces an unstable closed loop system. But a controller based on 16 or 22 modes seems to be adequate. When low level performance is required, i.e., low ρ value, a lower dimension model suffices.

Thus, it is clear that there exists an optimum size model for a given performance level.

RECENT RESULTS:

EFFECT OF DYNAMIC MODELING ON CONTROL OF LSS (Continued)



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RECENT RESULTS:
EFFECTS OF STRUCTURAL PARAMETERS ON CONTROL

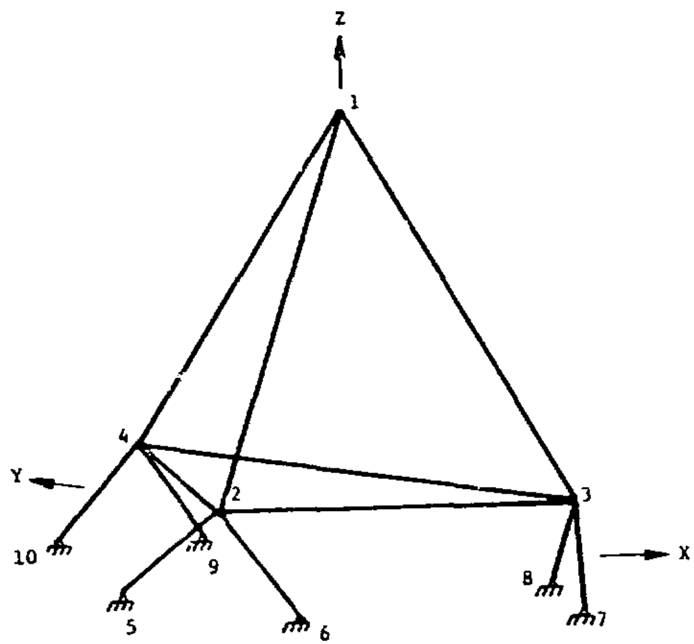
Some recent results in Reference (3) have shown that prudent modifications of a structure can help reduce the control problem. In Reference (3), four designs were studied. The figure shows the picture of the structure being studied and below this figure are listed four design cases. The table on the top-right-hand side lists the cross-sectional areas of various structural members and the total weight. The table below it lists the first few natural frequencies of the modes. The data clearly shows how redesigns help to increase and spread out frequencies. This will help the control design.

It is possible to modify the mode shapes by changing the structural parameters so that less control can be required. Recently, the Air Force Weapons Laboratory issued a PRDA to study this issue.

Reference:

(3) Khot, N.S., V.B. Venkayya, and F.E. Eastep," Structural Modifications of Large Flexible Structures to Improve Controllability," Proceedings of AIAA Guidance and Control Paper, AIAA 84-1906, pages 420-430.

RECENT RESULTS:
EFFECTS OF STRUCTURAL PARAMETERS ON CONTROL



DESIGN A - Nominal Structure

DESIGN B - Minimize LOS Error;
Weight Unchanged

DESIGN C - Minimize Weight; First
Two Frequencies Unchanged

DESIGN D - Same as C Except Weight
Scaled to Nominal Value

CROSS-SECTIONAL AREAS

ELEMENT NO.	DESIGN A	DESIGN B	DESIGN C	DESIGN D
1-2	1000.	993.5	122.74	353.17
2-3	1000.	614.9	242.96	712.86
1-3	100.	56.5	224.22	642.42
1-4	100.	453.3	224.25	643.50
2-4	1000.	352.6	242.93	712.77
3-4	1000.	909.0	133.90	392.35
2-5	100.	565.0	195.58	576.58
2-6	100.	873.0	195.60	576.64
3-7	100.	420.3	227.76	669.75
3-8	100.	763.0	124.78	366.53
4-9	100.	151.1	227.74	669.68
4-10	100.	727.0	124.80	366.60
Weight	.0437	.043	.0150	.0437

NATURAL FREQUENCIES

MODE	DESIGN A	DESIGN B	DESIGN C	DESIGN D
1	1.76	1.57	1.76	5.01
2	2.69	7.50	2.69	7.67
3	7.98	10.41	7.37	20.99
4	8.30	21.09	9.68	27.69
5	10.99	44.64	13.31	37.82

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RECENT RESULTS:
EFFECTS OF MATERIAL DAMPING ON CONTROL PERFORMANCE

These results are taken from the HR Textron 1984 IRAD Report. The figures on the left show a planar version of an antenna pivoted at the base and a simple finite element representation of the antenna. The pointing error due to rigid body rotation is the angle between the centerline and the open arrow (lower-left figure). The total (rigid plus flexible) line-of-sight pointing error is the angle between the centerline and the solid arrow.

A Linear Quadratic Gaussian method was used to generate a control law to minimize the error in line of sight. The control is applied through a torque at the pivot and it is assumed that full state feedback is available.

The figure on the right shows the effect of material damping, assumed to be viscous damping, on the total control energy. It clearly shows that higher damping can help in reducing the control energy. It also shows that beyond a certain level increasing damping does not help in reducing the control energy. Thus, there exists some optimum level of damping for a particular control problem.

The shape of the curve can be explained with physical arguments. At very low material damping (below 0.01%) the controller provides virtually all of the damping energy and material damping has little effect. At high material damping values (above 10%) the controller has almost no effect on vibration suppression, and the near-constant control energy level is that needed for rigid body control.

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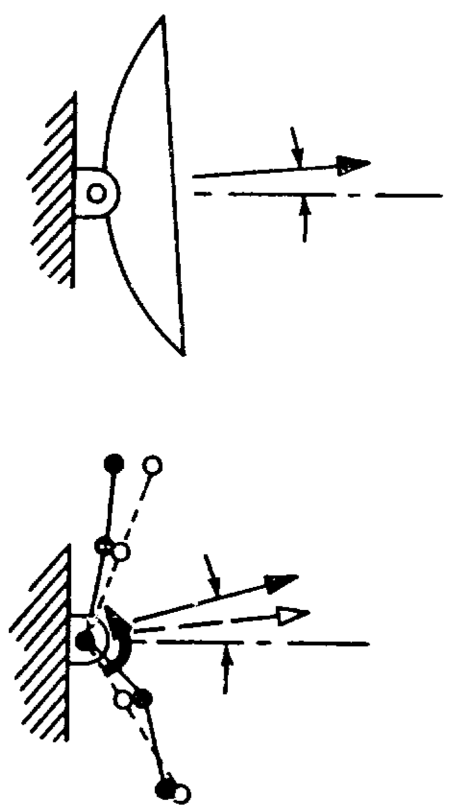
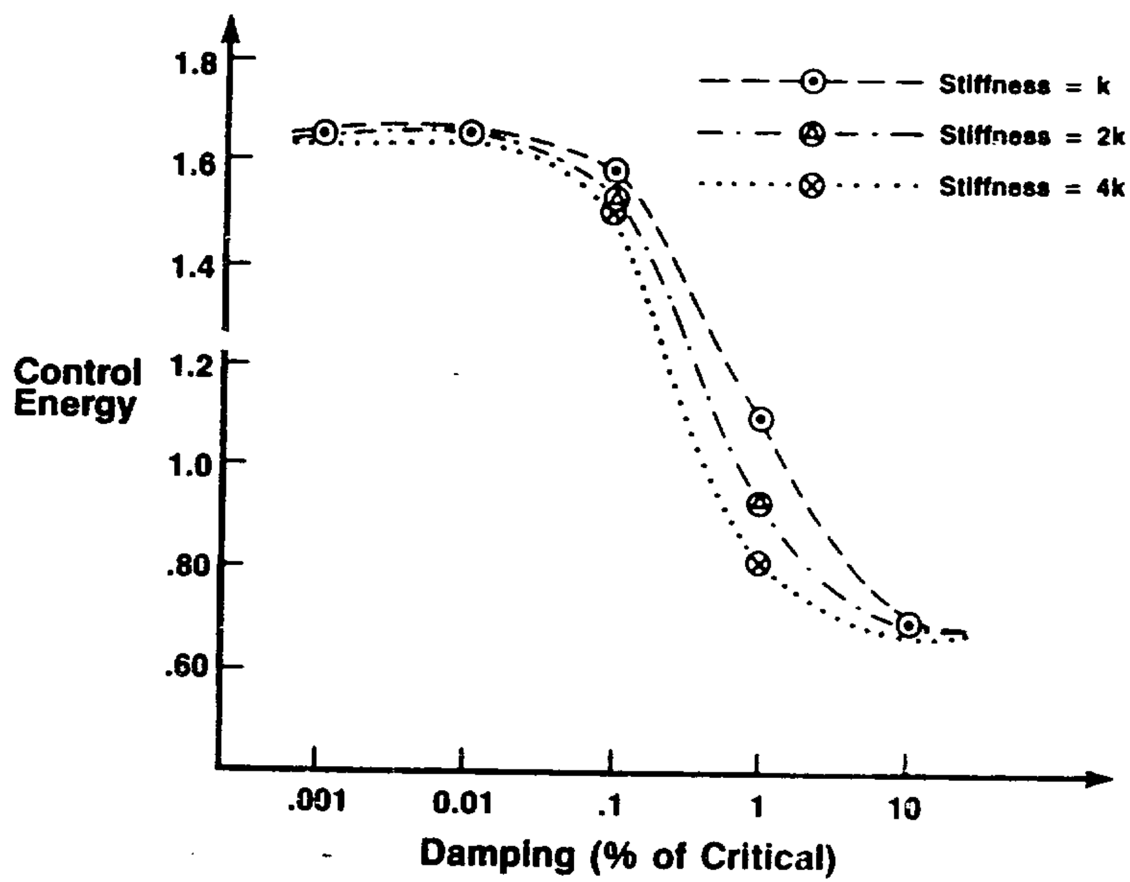
RECENT RESULTS:

Effects of Material Damping on Control Performance





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INTEGRATED DESIGN METHODOLOGY

All the previous discussions and results suggest that a new approach is needed to tackle the problem of controlling LSS.

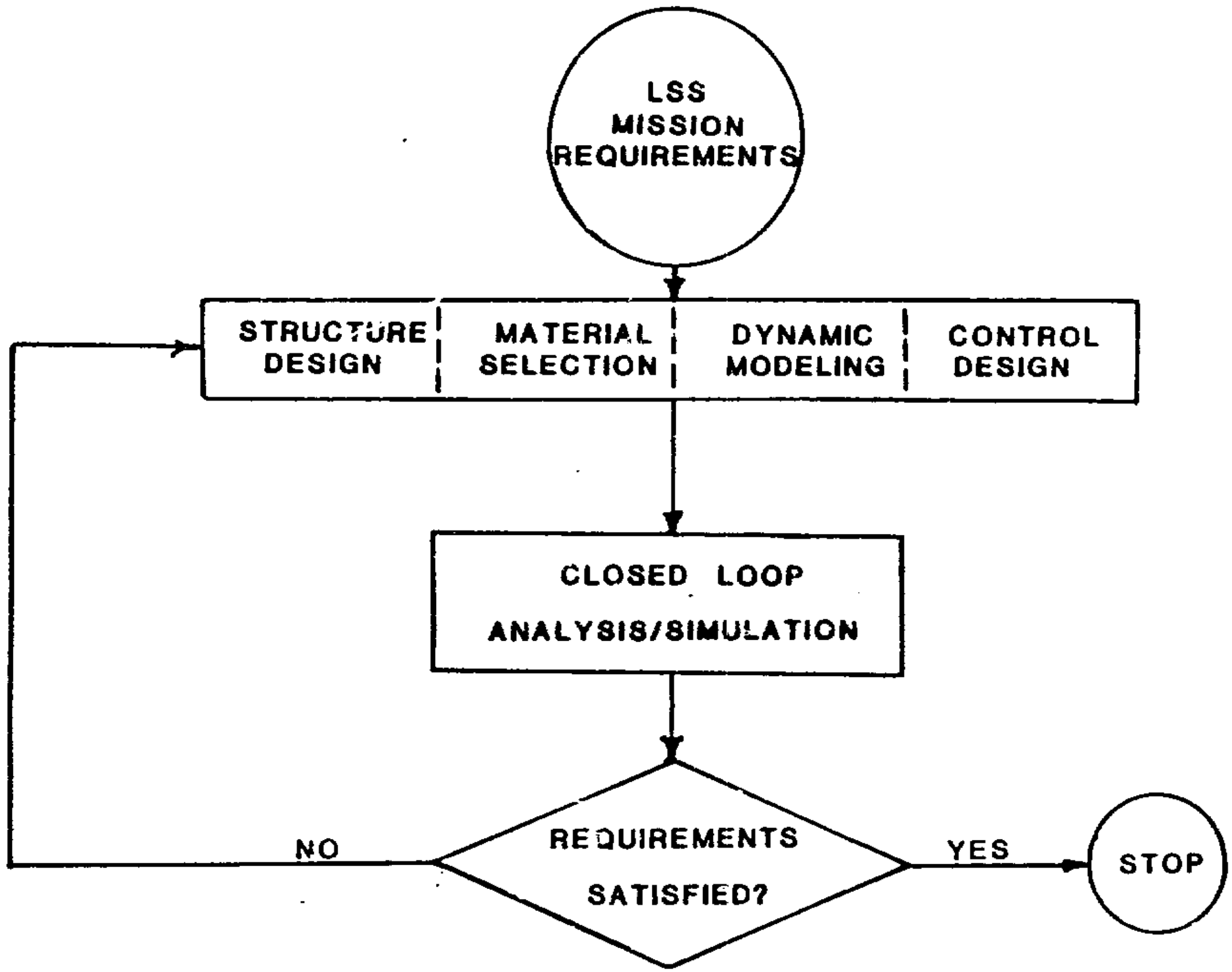
A new methodology is suggested. In fact the panel discussion on Interdisciplinary Issues in the Control of Flexible Structures, Reference (4), has alluded to this new methodology that is going to be addressed. The LSS mission requires an <u>integrated synthesis</u> of structure, materials, dynamic modeling and control design. The complicated nature of the problem forces this design methodology to be iterative. At each iteration a closed loop analysis and simulation are performed to check the fulfillment of the mission requirements. If they are not satisfied the program directs appropriate modifications of the structure, materials, dynamic modeling and control design to satisfy the mission goals. This completes one iteration cycle. At the end of all the necessary iterations a truly optimized system should emerge.

Thus, the integrated synthesis will generate an optimum high-performance system. The development of this method is an appropriate long-term goal for LSS control research.

Reference:

(4) Panel Discussion: Interdisciplinary Issues in the Control of Flexible Structures, JPL Workshop on Identification and Control of LSS, San Diego, California, June 4-6, 1984.

INTEGRATED DESIGN METHODOLOGY



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CURRENT STATUS OF INTEGRATED DESIGN SYNTHESIS

A recent literature search identified no research on the global integrated design synthesis methodology. Current research involves only two design variables at a time. For example, integrated design of structure and control or integrated design of dynamic model and control is pursued. Clearly, the goal of attaining complete integrated design synthesis will require much more effort.

The Air Force Weapons Laboratory at Kirtland Air Force Base is taking the initiative in integrated structure and control design. AFWL issued a PRDA in February 1985 on this topic. Gustafson, et al, Reference (5), are doing research in integrated structure and control design.

JPL is researching the problem of integrated dynamic modeling and control design. This research was carried out by HR Textron and UCLA, Reference (6). Currently, this research is being continued at UCLA. Dr. Skelton of Purdue University is also conducting research in this field, Reference (7).

These individual efforts must be continued to find the best approaches, and then the preferred approaches should be combined to solve the global design integration problem.

References:

(5) Gustafson, C.L., M. Aswani, A.L.Doran, G.T. Tseng, "ISAAC (Integrated Structural Analysis and Control) via Continuum Modeling and Distributed Frequency Domain Design Techniques," Proceedings of JPL Workshop on Identification and Control of Large Space Structures, San Diego, California, June 1984.

(6) HR Textron Report #956541-Final, Integrated Control/Structure Research for Large Space Structures, September 28, 1984.

(7) Skelton, R.E., "Optimization for Controllability," Proceedings of the Workshop on Modeling, Analysis, and Optimization Issues for Large Space Structures, Williamsburg, Virginia, May 13-14, 1982.

CURRENT STATUS OF INTEGRATED DESIGN SYNTHESIS

- NO RESEARCH ON INTEGRATED STRUCTURE, MATERIAL, DYNAMIC MODELING AND CONTROL DESIGN
- RESEARCH LIMITED TO INTEGRATED STRUCTURE AND CONTROL DESIGN AND INTEGRATED DYNAMIC MODELING AND CONTROL DESIGN
- INTEGRATED STRUCTURE AND CONTROL DESIGN INITIATIVE BY AIR FORCE WEAPONS LABORATORY
- JPL LED RESEARCH ON INTEGRATED DYNAMIC MODELING AND CONTROL DESIGN

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RESEARCH ON INTEGRATED DYNAMIC MODELING AND CONTROL DESIGN

COMPONENT COST ANALYSIS (CCA) APPROACH

This technique has been developed by Professor Skelton at Purdue University. It has been used to obtain an optimally sized model for a given control optimization criterion, Reference (7). If the system is linear and the control optimization criterion is quadratic, CCA gives a closed form solution which indicates which modes are unimportant from the point of view of the optimal cost. Such modes can be deleted from the model and thus reduce the complexity. Professor Skelton has also used CCA technique to delete actuators and sensors which are ineffective, Reference (8). The drawbacks of this approach are: 1) at present there is no way of selecting node points for the dynamic model and 2) one needs to start with a big model which is cumbersome.

FUNCTIONAL GAIN APPROACH

Functional gains for a controller is a concept that is applied to distributed parameter systems, such as large space structures. The functional gains approach was developed under JPL contract by HR Textron and UCLA, Reference (6). By using proper approximation techniques, lumped parameter systems are obtained and corresponding approximate functional gains are obtained. As approximations become more and more accurate, approximate functional gains converge to the true functional gains. Thus, the convergence of the functional gains gives a quantitative measure of the appropriateness of the dynamic model. In this method one starts with a small model, and keeps on adding modes until the functional gains cease to change. UCLA is conducting research to select finite element model node points on the basis of functional gains. The disadvantage of the functional gains approach is that it gives an upper limit on the modes to be included. Therefore, other techniques such as Balanced Realizations need to be applied to simplify the model.

References:

(7) Skelton, R.E., "Optimization for Controllability," Proceedings of the workshop on Modeling, Analysis, and Optimization Issues for Large Space Structures, Williamsburg, Virginia, May 13-14, 1982.

(8) DeLorenzo, M.L. and R.E. Skelton, "Sensor/Actuator Selection for the constrained Variance Control Problem," Proceedings of the JPL Workshop on Identification and Control of LSS, June 4-7,1984 San Diego, California.

(6) HR Textron Report #9655610-Final, Integrated Control/Structure Research for Large Space Structures, September 28, 1984.

RESEARCH ON INTEGRATED DYNAMIC MODELING AND CONTROL DESIGN

- COMPONENT COST ANALYSIS APPROACH
  - ADVANTAGES
    - CLOSED FORM SOLUTIONS AVAILABLE
  - DISADVANTAGES
    - DOES NOT HELP TO SELECT NODE POINTS FOR THE STRUCTURAL MODEL
    - STARTS WITH A LARGE MODEL

- FUNCTIONAL GAIN APPROACH
  - ADVANTAGES
    - QUANTITATIVE RESULTS AVAILABLE
    - MAY HELP TO SELECT NODE POINTS FOR THE STRUCTURAL MODEL
    - STARTS WITH A SMALL MODEL
  - DISADVANTAGES
    - NEEDS BALANCED REALIZATION OR OTHER SIMILAR TECHNIQUES TO SIMPLIFY THE MODEL

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FUTURE RESEARCH DIRECTIONS -- NEAR TERM

A more fundamental and a very useful question that needs to be answered in the JPL Integrated Dynamic Modeling and Control Design (IDMCD) research is the following: How can one locate the minimum number of finite element node points to model a structure, such that a control design based on the model is appropriate for obtaining the desired performance? Locating the minimum number of node points needs to be done in an optimal way. The selection of node points will be performance driven.

The optimally located node points may also point out the way the structure can be changed to improve the control performance. This would help pave the way to the integrated design of structure, materials, dynamic modeling and control design.

IDMCD also involves selecting and locating actuators and sensors. Thus, the next logical step is to integrate optimal location of actuators and sensors with IDMCD. One must also consider the detection, isolation and reconfiguration of malfunctioning actuators and sensors in the design process.

JPL should develop a technology roadmap for integrated control/structure modeling and analysis. The roadmap should indicate specific technology developments needed to achieve long-term goals and the schedule for their completion. It should also show how IDMCD results will be combined with results of other researchers to achieve major long-term objectives.

FUTURE RESEACH DIRECTIONS — NEAR TERM

- 0 INTEGRATED FINITE ELEMENT MODEL AND CONTROL DESIGN
  - APPROPRIATE DYNAMIC MODEL WITH MINIMUM NUMBER OF NODE POINTS
  - CONTROL DESIGN
  - CRITICAL ELEMENT OF INTEGRATED DESIGN
- 0 OPTIMAL SELECTION OF ACTUATORS AND SENSORS ALONG WITH THE ABOVE PROBLEM
- 0 TECHNOLOGY ROADMAP

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FUTURE RESEARCH DIRECTIONS -- LONG TERM

JPL should take advantage of the insights developed in its integrated dynamic modeling and control design research and assume a key role in developing the integrated design and analysis techniques for LSS.

This can be accomplished by continuing current research in integrated dynamic modeling and control and combining these results with results of other researchers in a computer aided design package, which simultaneously optimizes the structure, materials, dynamic modeling and the control design. The first major long term goal should be the development of a computer aided design capability based on new design and analysis algorithms and standard software technology. Later, an expert system should be added to aid the design optimization process, because the evolution of an expert system is a logical outcome from the development of a computer aided design capability.

FUTURE RESEARCH DIRECTIONS — LONG TERM

- INTEGRATED DESIGN METHODOLOGY FOR STRUCTURE, MATERIALS, DYNAMIC MODELING AND CONTROL
- COMPUTER AIDED DESIGN CAPABILITY FOR THE INTEGRATED DESIGN METHODOLOGY
- EXPERT SYSTEM FOR THE INTEGRATED DESIGN

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SUMMARY

The classical way of designing a high performance control system is not suitable for LSS because of the severe interaction of structural modes with the compensator. It has been clearly demonstrated that the dynamic modeling of the structure is a critical issue in obtaining a proper control system. Also, it has been shown that proper design of a structure and material selection are of importance since they can reduce the control problem. Thus, in order to solve the control problem, one has to solve the integrated problem of structure, materials, dynamic modeling, and control design.

Researchers have recognized the interdependent nature of the problem, but. due to the complexity of the problem, they are looking into its many smaller subsets. For example, researchers at Aerospace Corporation are looking at only the integrated structure and control design problem, and the Air Force Weapons Laboratory is initiating a study of the integrated structure/control design problem. The integrated problem of dynamic modeling and control design is being rigorously pursued by JPL. The JPL/HR Textron/UCLA team has obtained some interesting results and is continuing further research in this field. Professor Skelton and his coworkers at Purdue University are tackling similar problems.

It is important for JPL to continue research in the integrated dynamic modeling and control problem, especially the problem of locating node points in an optimal way which will yield a proper dynamic model for a given performance requirement. This is important because it has been shown that a proper dynamic model is necessary to obtain proper control.

JPL should play a key role in pursuing research in the integrated design methodology and should support a program to solve the globally integrated problem. The first major long-term goal should be the development of computer aided engineering programs. They should be followed by the development of an expert system to aid design optimization

SUMMARY

- NEED FOR INTEGRATED STRUCTURE, MATERIAL, DYNAMIC MODEL AND CONTROL DESIGN
- CURRENT RESEARCH MOVING TOWARDS INTEGRATED DESIGN
- JPL PROGRAM IN INTEGRATED DYNAMIC MODELING/CONTROL DESIGN IS PROVIDING A CRITICAL PART OF INTEGRATED DESIGN TECHNIQUES
- LONG TERM GOAL: COMPUTER AIDED INTEGRATED DESIGN CULMINATING IN AN EXPERT SYSTEM

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